Force sensor

This invention relates to a force sensor according to the preamble of claim 1.

5   The present invention covers the field of measuring a force with a system in the micro- or nano-regime. Micro electro-mechanical force sensors are available in a plurality of principles. They differ by the detection mechanisms. Known sensors are based on piezoresistive, capacitive, tunnel

10   current or thermal principles. These know force sensors are relatively large, that is they have large dimensions as some multiples of 100 μm. Force sensors according to the state-of-the-art are disclosed in the documents [5] and [6], in which limits to its size that is limits to a further miniatu-

15   rization can be derived. In the context of the present invention force sensors are also denoted by «inertial sensors».

In paper [1] furthermore all the problems which arise due to the increasing miniaturization of force sensors are dis-

20   cussed. The principle of a capacitive force sensor is depicted in Fig. 4(a): Due to the influence of a force

$$F = m \cdot a \; ,$$

where m denotes the mass and a the effecting acceleration, a change Δx of the distance x_0 of two electrodes or plates A

25   will occur. The capacity C is also determined by the di-electric constant ε_0 as well as by number ε_r , which is determined by the dielectric material between the plates A. These capacitive sensors show in general a degradation of the resolution by miniaturization. This effect results one the

30   one hand from a not very suitable signal to noise ratio (SNR). On the other hand the actual cause is an over proportional scaling down of the forces as well as restrictions due to process limitations and design rules. They are also called miniaturization barriers. The

35   limitations prevent that the scaling down of forces can be compensated by a corresponding miniaturization of the distance x_0 of the electrodes.

A numeric example explains the draw back of the state-of-the-art sensor according to figure 4(a):

$x_0 = 1 \ \mu m$;

5 $\Delta x = 0,05 \ \mu m$;

$C_0 = 0.53 \ pF$;

$A = 6 \cdot 10^4 \ \mu m^2$.

The displacement of the plates by $\Delta x = 0,05 \ \mu m$ results in a relative change of capacitance $\Delta C_{rel} \approx 5\%$.

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Furthermore the increasing miniaturization of force sensors leads to the problem of a reduction of the gauge factor for measuring a force. For a capacitive force sensor a limit arises also in reduction of its seismic mass due to design
15 rules.

The present invention therefore addresses the problem due to the miniaturization of force sensors.

20 The object of the present invention is to overcome the problems presented by the prior force sensors, especially to the degradation of the resolution.

These problems resulting from a further miniaturization are
25 solved by a force sensor specified in claim 1.

By the proposed use of a nanostructure as e.g. a carbon nanotube a force sensor is provided, which increases significantly the sensitivity as well as the resolution. This im-
30 provements result from on the sensing principle based on quantum-mechanical effects. By a deformation of a nanostructure its electrical conductance is affected up to two orders of magnitude. This outstanding sensitivity of a nanostructure as e.g. a carbon nanotube is disclosed in [2].

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Further advantageous embodiments are given in dependant claims.

The invention will be now described in preferred embodiments
with reference to the accompanying drawings wherein:

figure 1   is a view of a first embodiment;
figure 2   is a view of a first embodiment, which allows a
             compensation of environmental effects;
figure 3(a), Fig. 3(b)
             show the principle of the deformation of a carbon
             nanotube;
figure 4(a) shows the principle of a known capacitive force
             sensor;
figure 4(b) discloses the principle of a force sensor accor-
             ding to the present invention;
figure 5   shows a carbon nanotube.

Figure 5 illustrates the topological structure of a carbon
nanotube. The aspect ratio of common carbon nanotubes is in
the range 50 .. 5000. An example of the length is given
below. Before explaining embodiments the properties of carbon
nanotubes are first briefly discussed and references to its
properties and production are given.

The invention becomes apparent by considering the sensitivity
of a carbon nanotube when being object of a deformation
caused by a force F. Sensitivity is in this context the ratio

$$\frac{\Delta G}{\Delta F}$$

where ΔG : change of conductance.
          ΔF : change of force.

For a carbon nanotube 3 the conductance G instead of the
capacitance C is the electrical property, which is affected
by the resulting deformation caused by a force. The
sensitivity of a carbon nanotube 3 is up to two orders of
magnitude compared to the sensitivity of a capacitive force
sensor. This outstanding sensitivity and its possible causes
are discussed and disclosed in the document [2].

Corresponding to the values given in the introduction of this
document the sensitivity of a force sensor 1 with a carbon
nanotube of height h is approximately as follows:

$$h \quad = 0,600 \; \mu m;$$

5      $$\Delta x \quad = 0,050 \; \mu m;$$

$$F \quad = 8 \; nN;$$

$$\Delta G_{rel} = 99\%.$$

In the publication [3] in an extensive manner the synthesis,
10   properties and possible applications of carbon nanotubes 3
are disclosed. The teachings of this document [3] are there-
fore here incorporated by reference to it.

The principle of a force sensor 1 according the present in-
15   vention is depicted in Fig. 3(a), 3(b) and 4(b). According to
the representation in Fig. 3(a) and 3(b) a force F acts on
carbon nanotube 5. A carbon nanotube 5 is carried or fixed
between two arms 4. The carbon nanotube 5 itself is part of a
electric circuit with a current I. A deformation Δx caused
20   by a force F perpendicular to the carbon nanotube 3 decreases
its conductance G. This results by a voltage driven measure-
ment in a lowering of current I. The amount of the current I
gives an indirect measure of the acting force F. By an exter-
nal circuitry and an appropriate calibration the size of the
25   force F can be displayed. The force F is either from an ex-
ternal source or caused by an movable element, which is a
part of the force sensor 1. The latter principle is depicted
in figure 4(b), where the movement of the element 7 is caused
by an acceleration.
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In table 1 shows an example of the dimensions and its para-
meters of a carbon nanotube, which is the basic element of
the present invention. The cited values correspond to those
disclosed in [2], the symbol S denotes the unit Siemens, the
35   unit for conductance G:

Dimension, parameter	Value
Length of a carbon nanotube	500 nm
force acting perpendicular to the axis of a carbon nanotube	8 nN
displacement, deformation Δx	50 nm
conductance change ΔG	$9 \cdot 10^{-6}$ S to $9 \cdot 10^{-8}$ S

Table 1: typical parameters of a carbon nanotube.

For a force sensor 1 according to the present invention the
5   carbon nanotube 3 may built on the basis of a chemical vapour
deposition process CVD as controlled growth on prepatterned
nanostructures. Details to this processes can be derived from
document [4].

10   Figure 1 shows a g-sensor 1 – acceleration sensor – as a
first embodiment of the present invention. The sensor 1
includes a U-shaped support 2 of two arms 4 carrying carbon
nanotube 3. The two arms 4 are electrically insulated at the
position 6, partly shown in figure 1. A moveable element 7 of
15   mass m is located between the arms 4. The moveable element 7
is provided with a cusp tip 11. A movement of the element 7
towards the carbon nanotube 3 is caused by a force F
determined by

        F = m·a,
20   where:
m   mass of element 7;
a   acceleration acting via sensor 1 on element 7.

Tip 11 transfers the force F on to the carbon nanotube 3, by
25   which force the carbon nanotube is mechanically stressed,
that is deformed by a value Δx.

Optionally (not shown in figure 1) the sensor 1 is provided
with at least one stop element in order to limit the movement
30   of element 7. These stop elements enable a improved shock

resistance of the sensor 1. Each arm 4 is provided with a cusp 5, on which the carbon nanotube 3 is mounted.

5   The stability of the moveable element 7 may be increased by at least one spring 8. The spring 8 serves also for the guidance of the moveable element 7

A further embodiment of the present invention is depicted in Figure 2 with a second nanotube 10. The second carbon nano-
10   tube 10 may not be deformed by a force F. The arrangement with a second nanotube 10 allows the compensation of environmental effects as e.g. temperature. The second carbon nanotube is in mounted to the arms 4 in the same manner as described above. However the second carbon nanotube 10 is elec-
15   trically insulated from the first one. The second carbon nanotube 10 is also part of an electric circuit with a current I . By an external circuitry this arrangement allows a common mode rejection, that is the above mentioned compensation of environmental effects. Also a possible defor-
20   mation of the support 2 can be compensated by using a second carbon nanotube 10

Force sensors and g-sensors according to the present invention are especially suitable for Vehicle dynamic control
25   systems, but this example of application is not limiting at all.

The outstanding sensitivity of a g-sensor 1 according to the present invention allows the detection of very small accele-
30   rations, which opens a broad field of applications.

The invention is not limited to the embodiment depicted above with a carbon nanotube. The invention can also be carried out with other elements which have similar properties as carbon
35   nanotube. Another example is a bor-nitride nanotube. It shows a huge change in electrical and optical properties by mechanical deformation as it has been shown for carbon nanotubes

[1]. In a more general context nanotubes count to the mate-
rial class of quasi one-dimensional (1D) nanostructures which
are characterized by the confinement of electrons in two
spatial directions. These strong effects even hold for a big
5   class of nanostructures where local atomic bonds determine
the electrical and optical properties.

Therefore in this paper the elements
- carbon nanotubes,
10   - nanotubes,
- quasi one-dimensional (1D) nanostructures
are summarized by the general term «nanostructure».

15   **List of reference numerals**

1   force sensor, inertial sensor

2   support

3   carbon nanotube, nanotube, bor-nitride nanotubes,
       quasi one-dimensional (1D) nanostructures;
20   nanostructure

4   arm

5   cusp at the arm 4, mounting point of a carbon nanotube

6   insulation

7   moveable element, mass

25   8   spring

9   insulation between nanotube 3 and 10

10   second carbon nanotube, second nanotube, second bor-
       nitride nanotubes, second quasi one-dimensional (1D)
       nanostructures; second nanostructure

30   11   tip of the moveable element 7

list of symbols

a   acceleration [m/s^2]

ε_0 dielectric constant

ε_r relative dielectric constant

5   F   force

G   conductance

m   mass [g]

x_0 distance, e.g. [μm or nm]

Δx displacement, e.g. [μm or nm]

10 ΔC change of capacity.

ΔF change of force.

ΔG change of conductance

list of acronyms

CNT carbon nanotube

15 CVD chemical vapour deposition

MEMS Microelectromechanical systems

SNR Signal to noise ratio

VDC Vehicle dynamic control

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